Financing the Energy Transition

Solar Memo

July 2024

Contents

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1. Executive summary

*This report is the second in a series from JFI's **Financing the Energy Transition** initiative, pairing market analysis with levelized-cost-of-energy modeling to evaluate how trade and industrial policy are interacting with market forces to shape the transition to a low-carbon economy.*

US solar policy is on track to completely displace imported solar modules, thanks to a combination of tariffs on imports and tax credits for domestic manufacturing. The trade-offs of onshoring module assembly, in terms of the cost of solar energy, appear modest.

However, access to imported upstream solar materials (cells, wafers, etc.) remains critical, and **domestic module prices** will likely continue to be roughly twice Chinese benchmarks.

Key points:

- *Solar deployment in the US is growing at a rapid pace.*

  Capacity additions across both distributed and utility-scale solar projects reached 40 GW_{dc} in 2023 — up from 23 GW_{dc} the year before. With ~48 GW_{dc} of planned utility-scale projects coming online in 2024,[1] overall deployment is likely to exceed 50 GW_{dc}.[2] Delivering on the high end of forecasts for both electricity supply growth and solar's share of US generation requires further acceleration to 50-80 GW_{dc} per year.

- *The US currently imports the vast majority of its solar panels from four countries in Southeast Asia (SEA).*

  Completed module (i.e. "panel") imports totaled 54 GW_{dc} in 2023, per customs data, ~1.7x the rate of US solar deployment and over 4x domestic module manufacturing capacity.[3] Last year, 80% of module imports came from four countries: Cambodia, Malaysia, Thailand, and Vietnam.

- *The SEA-to-US trade route drives much higher solar panel prices versus Chinese benchmarks.*

[1] Based on year-to-date capacity additions of 9.5 GW_{ac}, additional planned projects totaling 27.5 GW_{ac}, and an assumed inverter loading ratio (ILR) of 1.29 – all based on the EIA Electric Generator Monthly Inventory.

[2] The Q1 2024 run rate for residential, commercial, and community-scale capacity additions implies roughly 8 GW_{dc} of growth this year, down 20% from 2023.

[3] Based on a full-year average of domestic module manufacturing capacity in 2023, as reported by the Solar Energy Industries Association (SEIA).

The average customs value of imported modules is \$322 per kW_{dc}, or \$170 per kW_{dc} for cells not assembled into modules.[4] This represents a 111% or 105% premium relative to Chinese benchmark prices, respectively.

- *Solar trade flows are already heavily influenced by trade and industrial policy.*

  In particular, tariffs and restrictions on solar panels with Chinese content have shifted final assembly of panels for the US market to Southeast Asia — the share of US module imports coming from China peaked at 57% in 2014, and in recent years has fallen to < 1%.

- *The latest wave of solar policy changes will shift final assembly from SEA to the US at a staggering pace.*

  Over the last 18 months, 24 GW_{dc} of US module manufacturing capacity came online — representing a 4x increase in capacity versus the start of 2023. An additional 24 GW_{dc} is under construction, and 18 GW_{dc} of capacity is at the planning stage. Combined, this pipeline will make the US **self-sufficient** in module supplies over the next 1–2 years.

- *Our modeling shows that thanks to the 45X tax credit, the* ***minimum sustaining cost*** *of domestic modules will be* ***competitive with SEA import prices,*** *particularly with the SEA tariff bridge and bifacial module exemptions sunsetting.*

  At 80% utilization, the prices required for manufacturers to earn an adequate return on their investment could range from \$313–438 per kW_{dc}, representing anywhere from a 5–50% premium to recent import prices.

- *Because modules represent less than one third of the levelized cost of electricity (LCOE) from utility-scale solar, the cost/benefit of onshoring module production is favorably skewed.*

  Upfront construction costs total around 72% of the lifetime cost of solar power, or approximately 90% when including debt service and a return n capital for developers. Modules represent approximately 30% of construction costs and therefore 27–28% of the lifetime cost of solar power. Thus, every +/- 10% move in module prices translates to only a +/- 3% difference in average energy costs.

- ***Despite the ramp-up in domestic module capacity, the US is likely to remain a structural importer of upstream materials*** *(cells, ingots/wafers, and polysilicon).*

[4] Trailing 12-month average, based on customs data.

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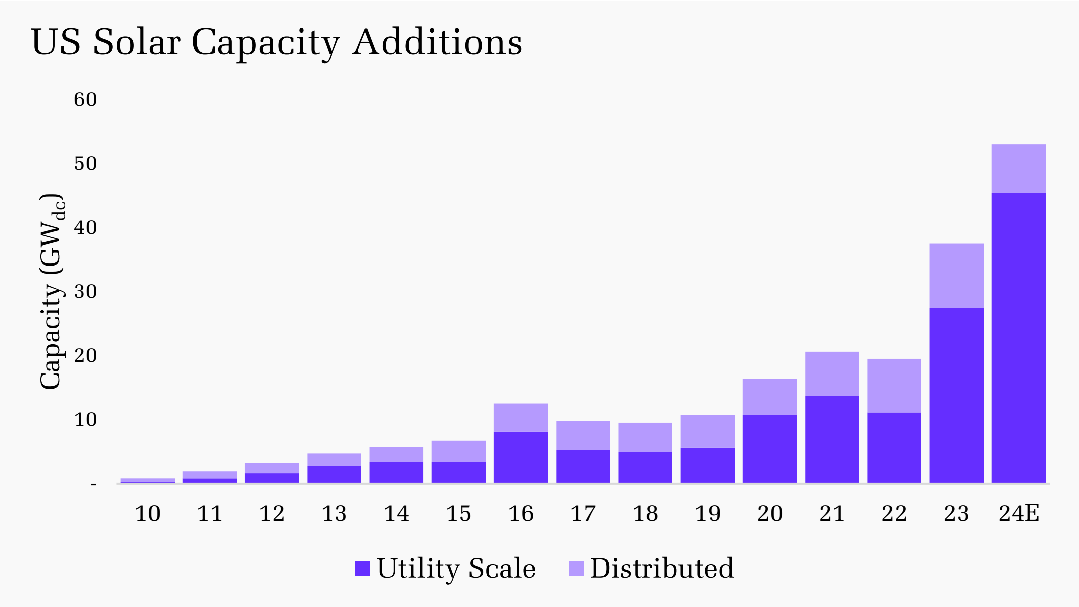
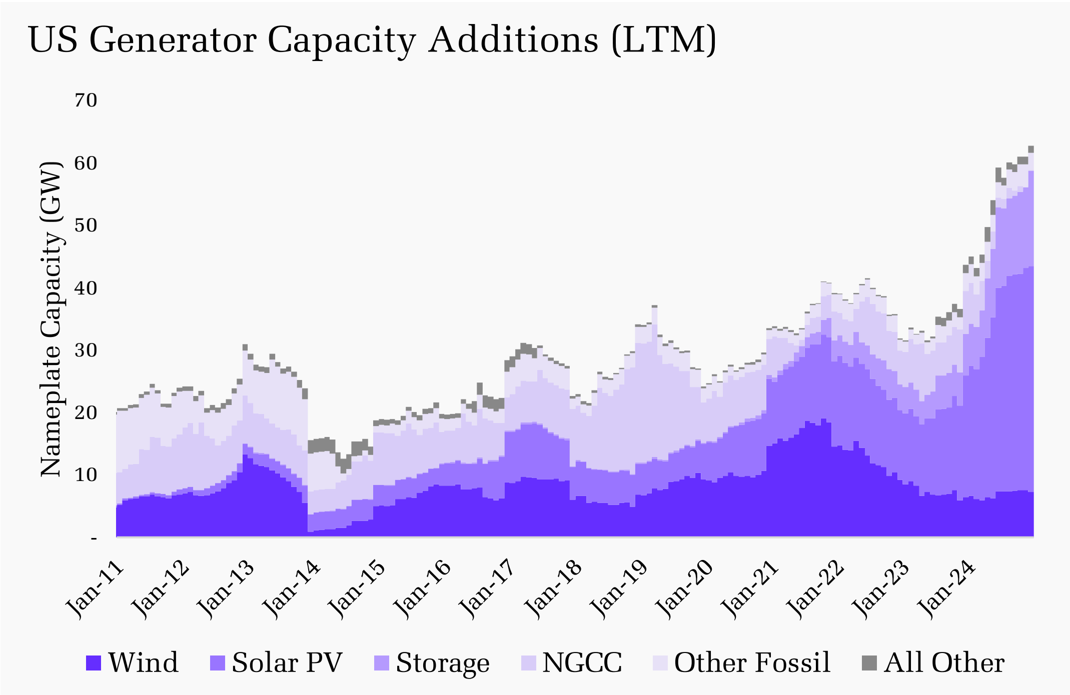
Project announcements for domestic manufacturing of crystalline silicon (c-Si) solar cells (25 GW_{dc}), wafers (14 GW_{dc}) and ingots (8 GW_{dc}) have been much more muted than for module production. These projects are, on average, at a much earlier stage than module manufacturing projects, with no more than 20–40% actually under construction, depending on the process stage.

2. Deployment trends



(US EIA, NREL)

Solar is by far the fastest growing power generation technology in the US. Utility-scale solar projects are on track to reach 58% of total US generator capacity additions in 2024, at 36 GW_{ac}. Solar and storage combined are expected to reach **82%** of capacity additions. **Annual utility-scale capacity growth is up by > 150x relative to 2010,** when solar only made up 1% of new power plant capacity.



(US EIA)

US solar electricity share in 2030:

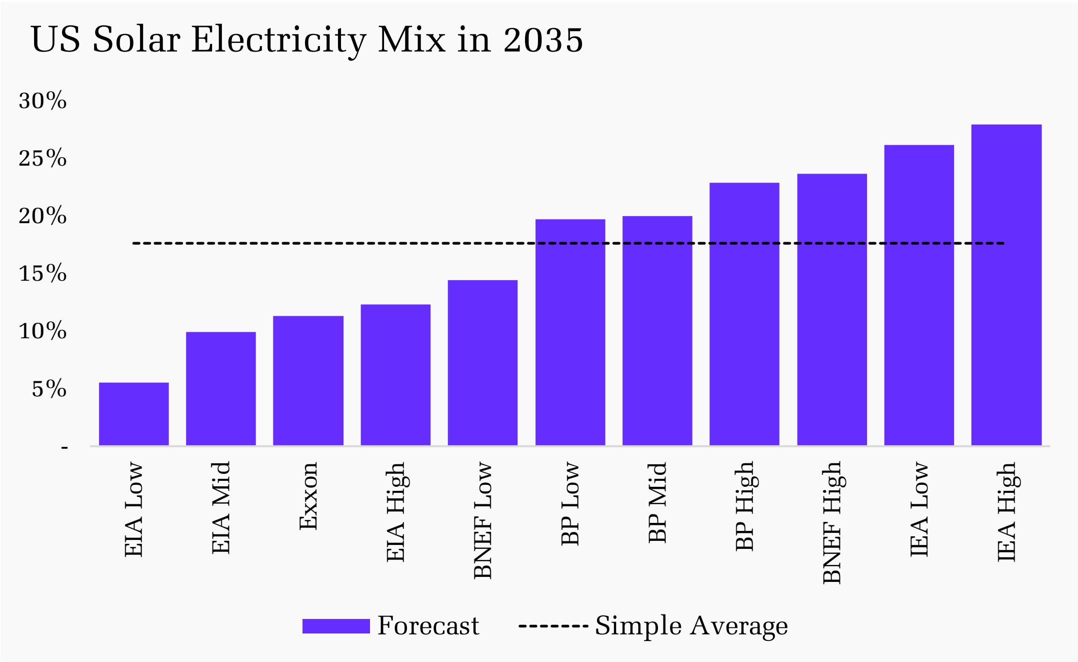
		Key Assumptions:				US Electricity Supply Growth *(Annualized)*					
		2035 Capacity (TW)	ILR (DC/AC)	Capacity Factor (%)	Gen'n. (TWh)	**1.5%**	**2.0%**	**2.5%**	**3.0%**	**3.5%**	**4.0%**
Annual Solar Add'ns. (GW_{dc})	**50**	0.73	1.25	19.9%	1,022	20.1%	19.0%	17.9%	16.9%	15.9%	15.0%
	55	0.79	1.25	19.9%	1,106	21.8%	20.5%	19.3%	18.2%	17.2%	16.2%
	60	0.85	1.25	19.9%	1,189	23.4%	22.1%	20.8%	19.6%	18.5%	17.5%
	65	0.91	1.25	19.9%	1,273	25.0%	23.6%	22.3%	21.0%	19.8%	18.7%
	70	0.97	1.25	19.9%	1,356	26.7%	25.2%	23.7%	22.4%	21.1%	19.9%
	75	1.03	1.25	19.9%	1,440	28.3%	26.7%	25.2%	23.8%	22.4%	21.2%
	80	1.09	1.25	19.9%	1,523	30.0%	28.3%	26.6%	25.1%	23.7%	22.4%

US electricity demand was broadly flat from 2007 to 2023. Looking ahead, the arrival of new loads (data centers, EV charging, heat pumps, onshoring industry etc.) is expected to drive faster growth.

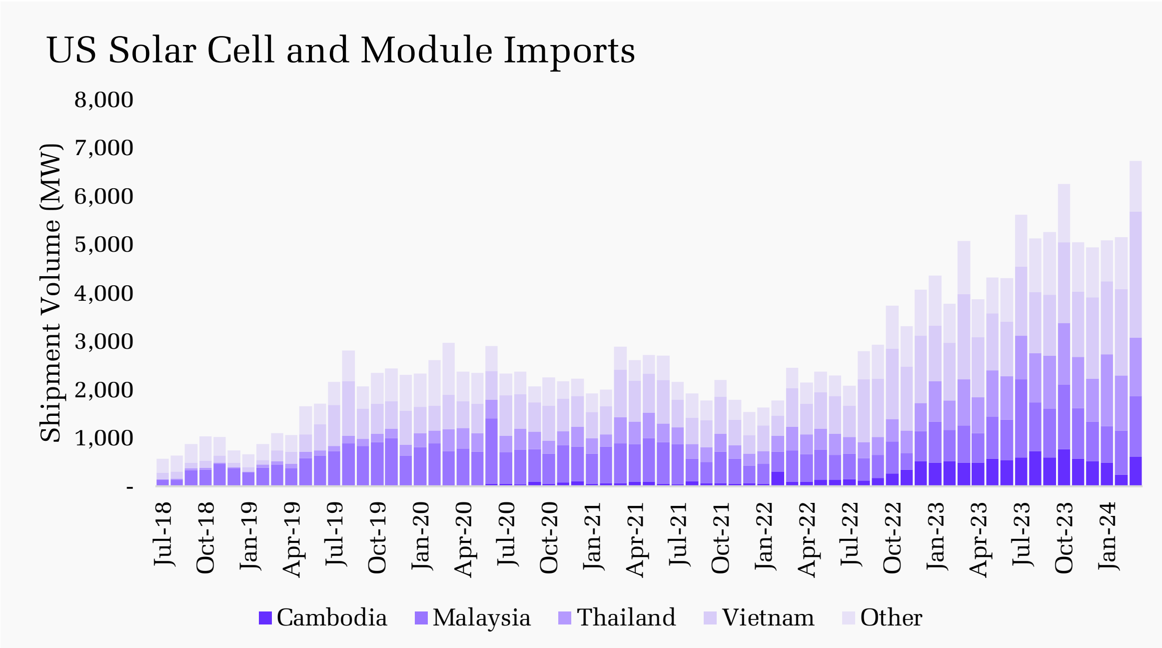
The IEA's *Electricity 2024* projects US electricity demand growing by 1.5% per year from 2024 to 2026, while the EIA's *Short-Term Energy Outlook* forecasts 2.8% growth in 2024, decelerating to 1.9% in 2025. More granular estimates from independent system operators (ISOs) in some regions of the country call for longerterm electricity demand growth in the 2.0–2.5% range (e.g. PJM, ERCOT, and CAISO).

While many long-term energy outlooks predict that solar will represent less than 20% of US electricity supply in 2035, this increasingly seems too low. Current deployment trends of roughly 50 GW_{dc} per year, and consensus electricity demand growth of 2.0–2.5% would imply a solar share of 18–20% in 2035 — the target date for the White House's goal to reach "carbon pollution-free electricity."

But deployment will have to be higher than that for the market to absorb the **72 GW_{dc}** of domestic module manufacturing capacity that will be online within the next couple of years. Our base case is that **annual module deployment exceeds 70 GW_{dc}** by the 2025/2026 time frame, and that **electricity demand grows faster than many modelers expect,** at 2.5–3.5% per year. This implies a solar share of 20–25% of electricity.



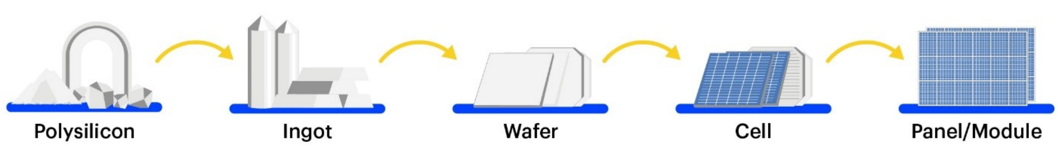
3. Trade flows and module prices



(US ITC DataWeb)

Over the last 12 months, 80% of solar cells and modules imported to the US came from four key SEA countries — Cambodia, Malaysia, Thailand, and Vietnam. In absolute terms, imports totaled **62 GW_{dc},** approximately ~1.7x the amount of panels installed in 2023, and ~1.2x the amount installed in 2024. Imports also dwarfed domestic module manufacturing capacity, which has grown from ~8 GW_{dc} per year to ~32 GW_{dc} as of Q1 2024.

Solar panel production can be broken down into four key steps — **polysilicon, ingots and wafers, cells, and modules.** Manufacturers **purify metallic silicon** to produce polysilicon, **grow crystalline ingots and slice them into µm-thin wafers,** treat wafers to turn them into photovoltaic cells, and assemble cells into complete modules.

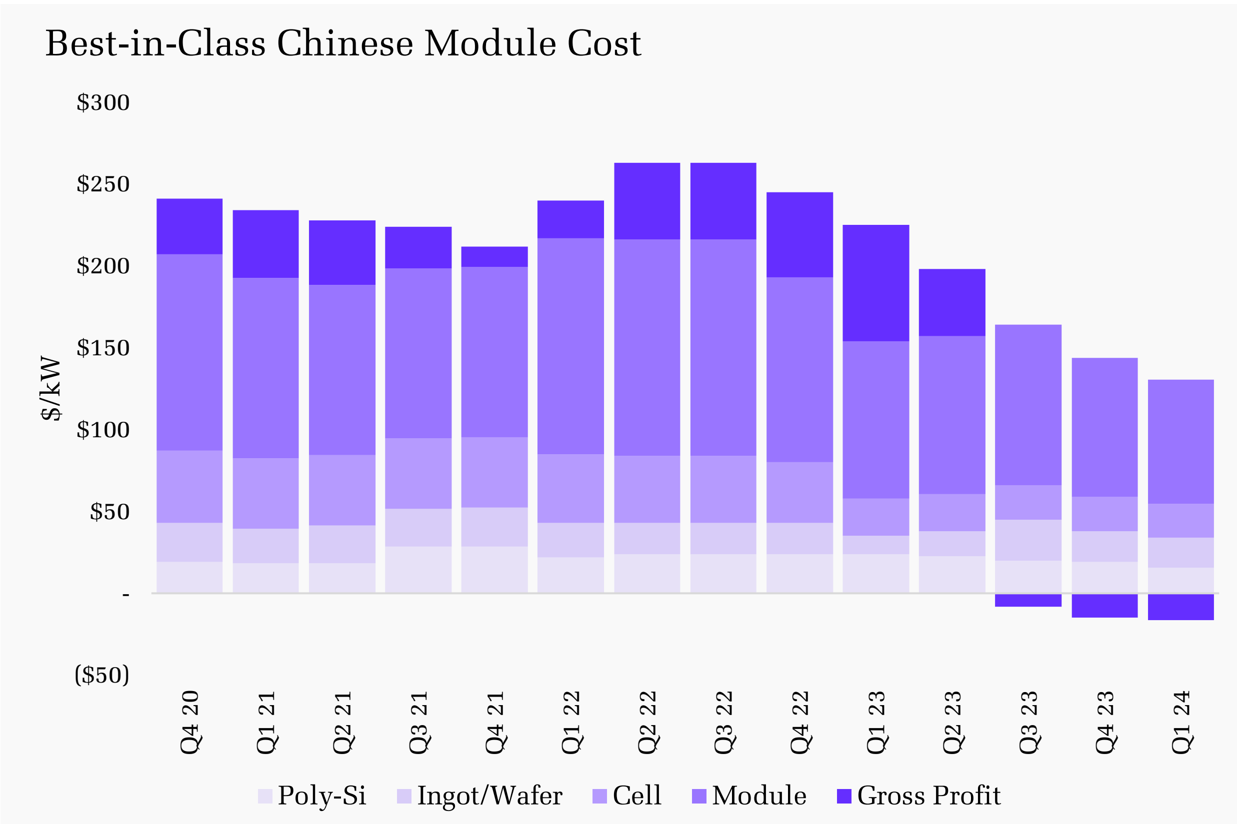


(IEA)

Per BNEF data, best-in-class, vertically integrated Chinese original equipment manufacturers (OEMs) are currently selling solar modules for just $114 per kW_{dc}. However, this price reflects severe oversupply at the downstream (module) end of the manufacturing process, with vertically-integrated producers operating at negative gross margins.

Analysis of the financial statements of publicly traded Chinese OEMs suggests a long-run breakeven cost (allowing for an adequate return on capital employed) **directionally closer to $150 per kW$_{dc}$.**

Further adjusting for polysilicon not sourced from the Xinjiang Autonomous Region would imply **costs of around $180 per kW$_{dc}$.** While higher than recent spot module prices, this would still leave the Chinese solar OEMs as, by far, the lowest-cost producers globally.

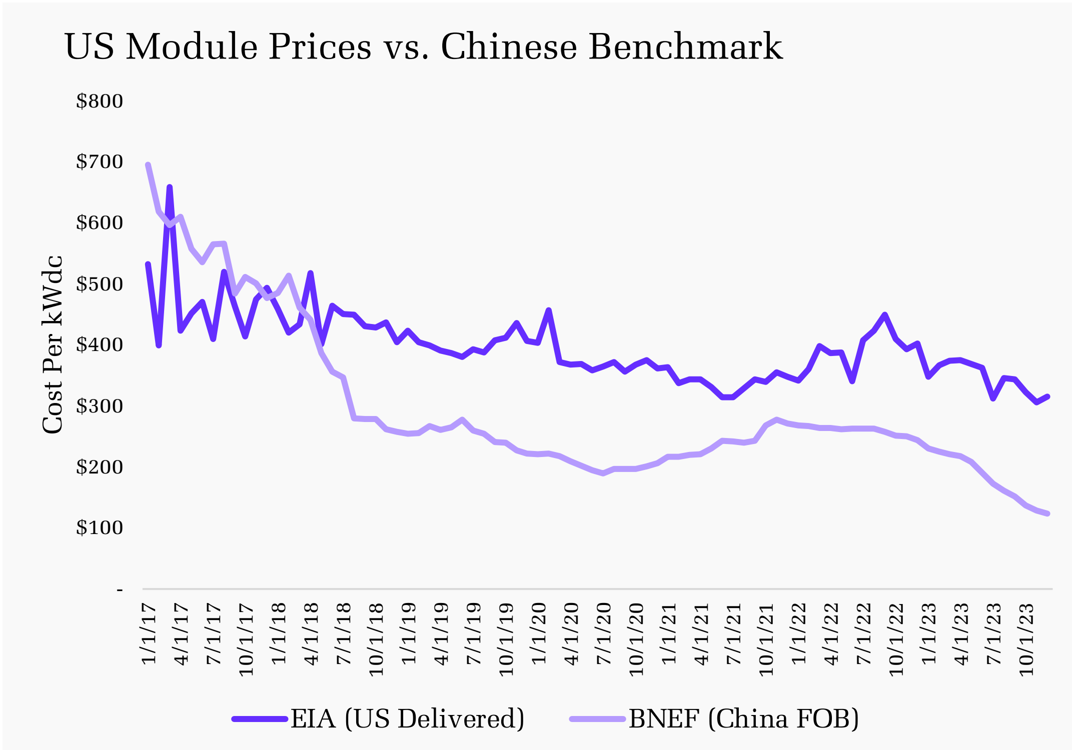


(BNEF)

Over the last 12 months, the customs value of modules imported to the US from the four key SEA countries was **$322 per kW$_{dc}$**, versus an average customs value of **$170 per kW$_{dc}$** for cells not assembled into modules. These prices are +111% and +105% higher than the average price of modules and cells in China, respectively.

Only 40–50% of the premium for cells, and 20–25% of the premium for modules, can be explained by higher prices for polysilicon not sourced from the Xinjiang Autonomous Region of China, which effectively cannot enter the US because of the

Uyghur Forced Labor Protection Act (UFLPA).[5] The remainder can be attributed to higher costs for other inputs in SEA, and, perhaps, profits for suppliers able to tap into the US market.



(BNEF, EIA)

[5] This calculation assumes a $15-20 premium per kg for UFLPA-compliant polysilicon, and polysilicon content in c-Si solar modules of 2.16 kg per kW_{dc}.

4. Tariffs and duties

Chinese imports peaked as a share of US solar shipments in 2014, at 57 percent, and, over the last 12 months, they made up less than 1 percent of imports, at a little over 500 MW. Under the Trade Act of 1974, the executive branch has significant discretion in applying import duties and other trade restrictions if imports are found to pose a “threat of serious injury” to US industry (Section 201 Tariffs) or in retaliation for violating trade agreements (Section 301 Tariffs).

The Trump administration applied a **30 percent tariff** on solar imports above a 2.5 GW quota, beginning in February 2018, following a US International Trade Commission (ITC) investigation of a complaint brought by domestic solar manufacturers.

More recently, in August 2023, the ITC found that several SEA-based manufacturers were circumventing tariffs on Chinese solar imports, and, in April 2024, a group of domestic solar manufacturers petitioned the ITC for AD/CVD relief from SEA-origin solar imports, claiming they needed protection from imports priced below their economic cost.

In addition, the Biden administration has increased the headline tariff rate on Chinese solar imports from 25 to 50 percent, and confirmed that two existing tariff exemptions — for two-sided (“bifacial” solar modules), and for Southeast Asian imports — will come to an end as planned this June. This will have a large impact on the actual prices paid by US customers, since nearly all solar panel imports over the last two years have benefited from one or both of these exemptions, bringing the actual tariff levied on solar imports close to zero.

The current tariff petition aimed at SEA-origin imports alleges extremely high dumping margins. It is hard to quantify the possible range of outcomes from the case (a readout is expected later this year).

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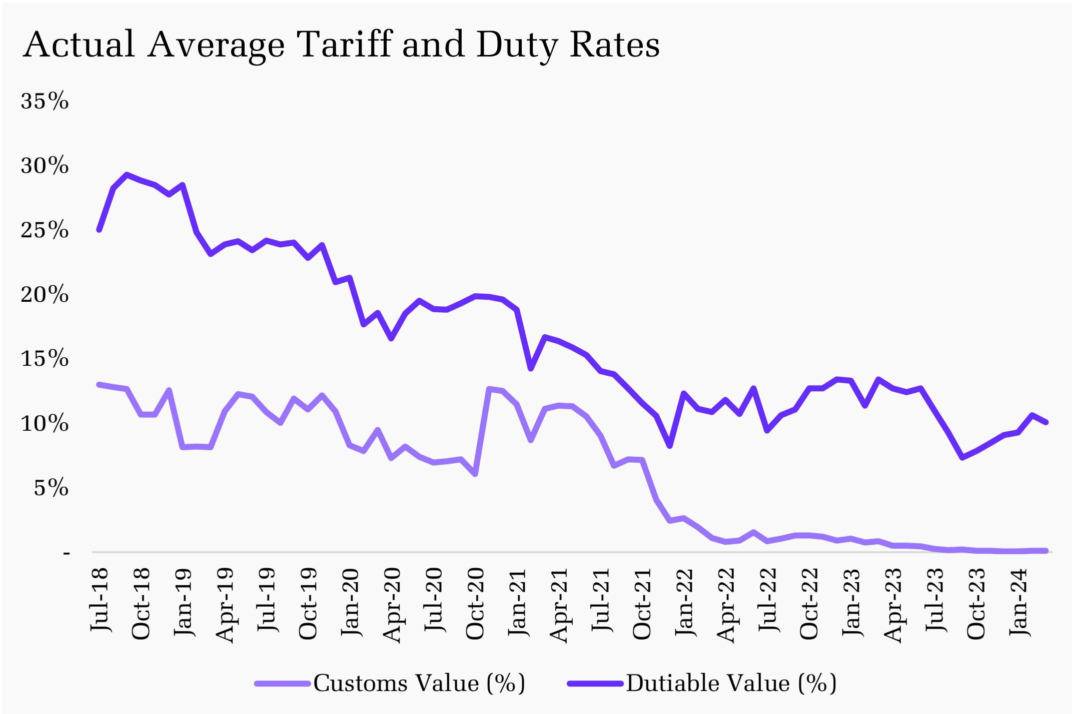
Exporting Country	Cell and Module Imports (GW)	Customs Value ($bn)	Average Price ($/kW)	Alleged Dumping Margin (%)	Implied "Normal" Price ($/kW)
Vietnam	16.3	$4.84	$297	271.5%	$1,104
Malaysia	11.4	$3.14	$275	81.2%	$499
Thailand	11.2	$4.09	$364	70.4%	$620
Cambodia	6.9	$2.38	$346	126.1%	$782
SE Asia	**45.8**	**$14.45**	**$315**	**149.3%**	**$786**
South Korea	3.9	$1.28	$329		
India	3.9	$1.86	$473		
Singapore	0.8	$0.43	$558		
All Other	3.5	$1.24	$354		
Rest of World	12.1	$4.82	$397		
Global Total	58.0	19.3	$332		

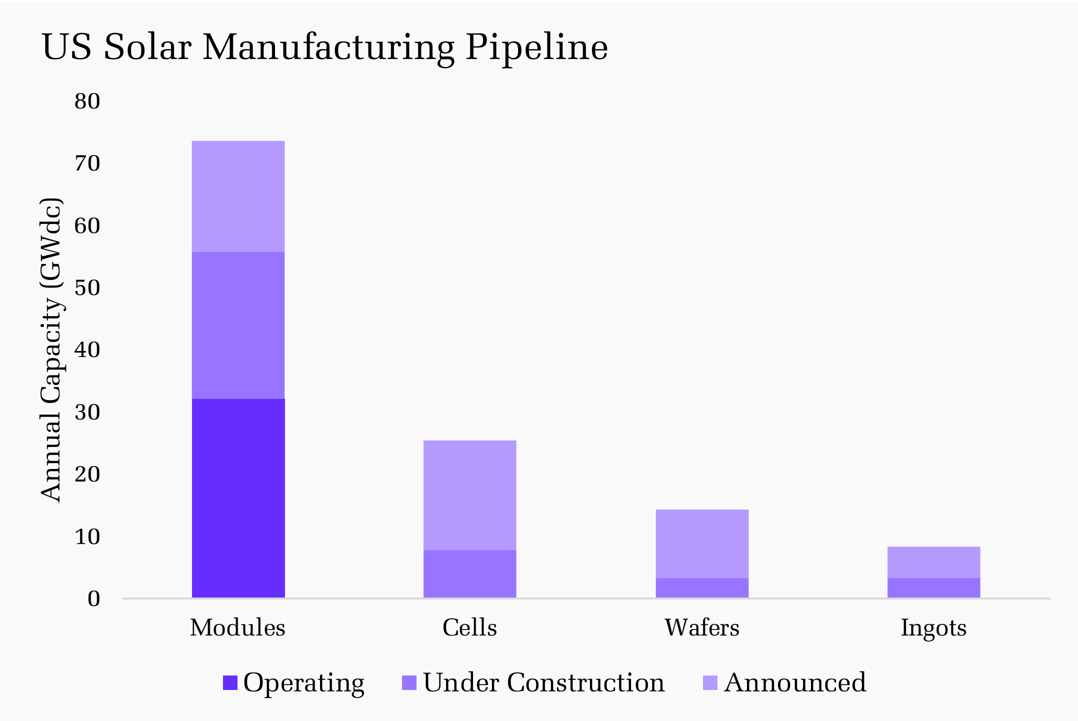
Over the last two years, the combination of the bifacial module exemption and SEA tariff bridge brought the actual tariff rate applied to US solar module imports close to 0%. It seems reasonable to expect that, at a minimum, the gap between tariffs and duties as a percentage of *customs value* (the actual value of imported merchandise) and as a percentage of *dutiable value* (the value that tariffs and duties apply to) will close, adding a 10–15% premium for imported panels (roughly $30–50 per kW_{dc}).



(US ITC DataWeb)

5. Onshoring trends

Per data from the Solar Energy Industries Association (SEIA), **US module manufacturing capacity has quadrupled over the last 12–15 months,** and is on track to more than double again by 2025–2026. This rapid build-out of domestic capacity is likely to **more than cover** the amount of module capacity needed to drive a 4–5x increase in solar's share of US electricity supply between now and 2035.

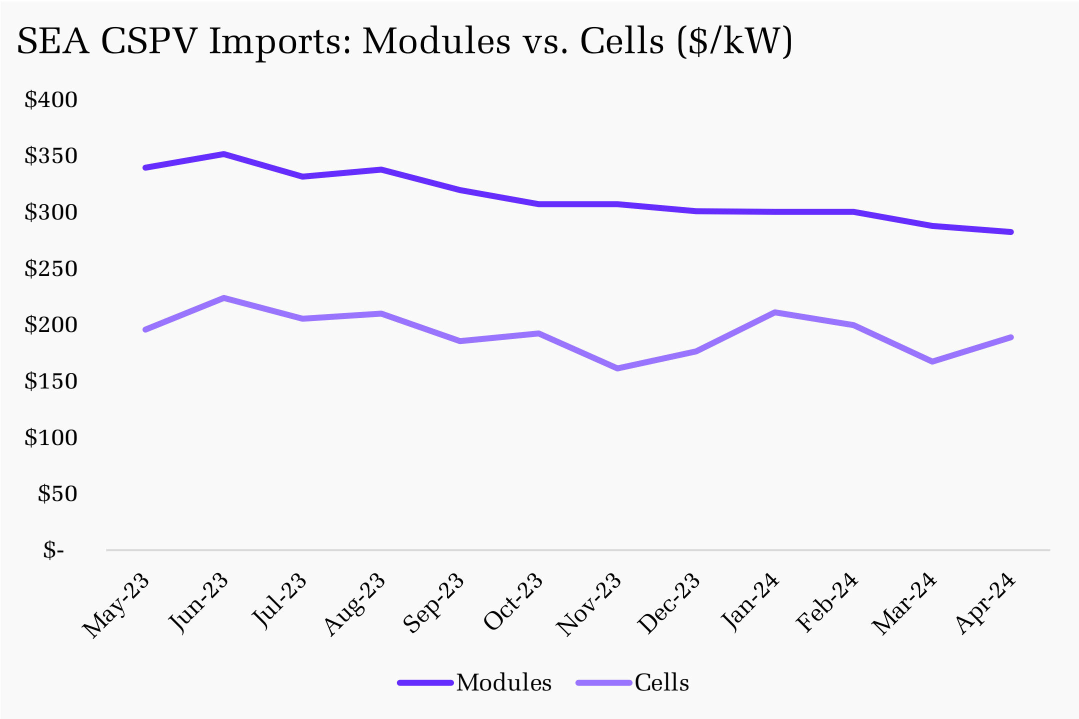


(SEIA)

6. Onshoring cost breakdown

In recent months, the customs value of modules imported directly from the four key SEA exporters has averaged ~$300 per kW_{dc}, versus ~$200 or less per kW_{dc} for cells alone. Shifting the economic benefits of this ~$100-120 per kW_{dc} gap onshore — which essentially consists of raw materials and labor added to the cells, plus a return on capital for manufacturers — appears to be the primary goal of US solar policy.

We estimate that with the 45X tax credit, domestic module manufacturers will be competitive with SEA imports, though at the prices they need to realize to recoup their investment in plant and equipment, prices will still be 2–3x that of best-in-class Chinese manufacturers. **In essence, US policy has rapidly succeeded in its apparent goal –** to claw back the ~$120 per kW_{dc} margin earned by SEA-based module manufacturers, and reallocate it to domestic manufacturers, workers, and suppliers.[6]



(US ITC DataWeb)

The 45X tax credits are enormous relative to the all-in cost of a utility-scale solar installation. The **$0.07 per W_{dc} credit for modules** is particularly notable, because it covers 60–70% of the additional cost of assembling cells into modules.

A sensitivity analysis based on a bottoms-up cash flow model for an illustrative module manufacturing project suggests that the selling price required for

[6] $120 is the rough difference in customs value per kW between the price of finished modules and cells imported from the four key SEA countries of origin between May 2023 and April 2024.

manufacturers to earn an adequate return on investment is **$313–438 per kW_{dc}**, which translates to a 5–48% premium, relative to recent import prices, even under very conservative assumptions on production costs relative to best-in-class Chinese producers.

(c - Required US module price [1] [2] [3], in $/$kW_{dc}$

		Capex ($/kW)		
		$80	$100	$120
Module Process Cost [5] vs. China	-	$313	$319	$326
	+50%	$341	$347	$354
	+100%	$369	$376	$382
	+150%	$397	$404	$410
	+200%	$425	$432	$438

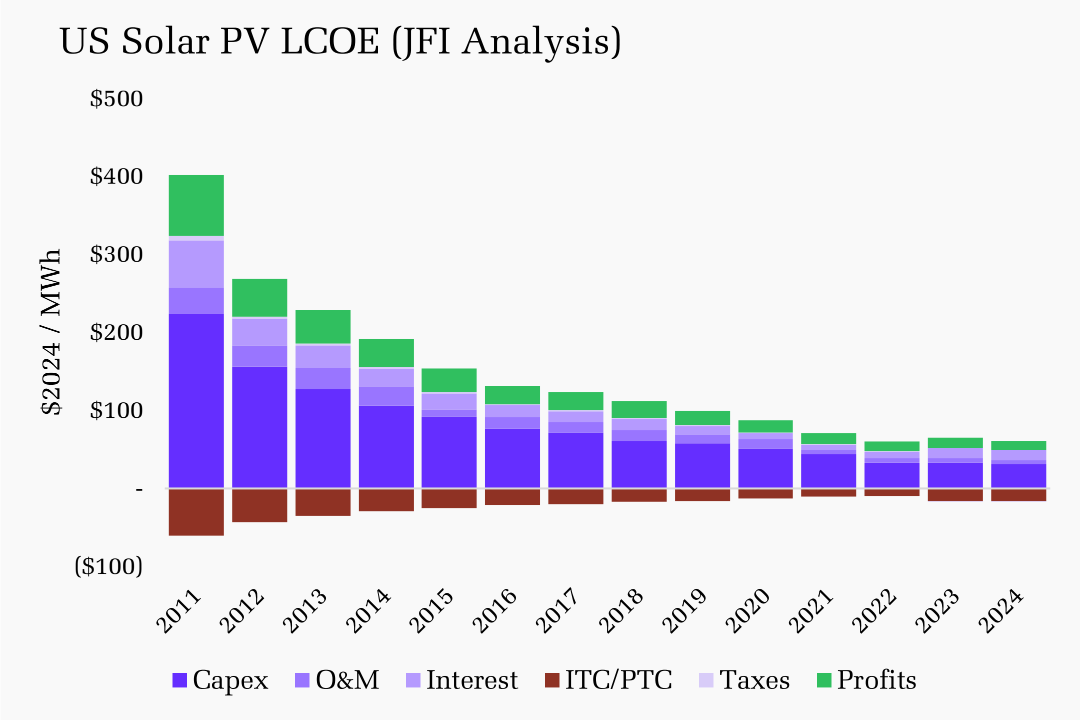
(d - Variance versus recent[2] import prices (%)

		Capex ($/kW)		
		$80	$100	$120
Module Process Cost [5] vs. China	-	5.4%	7.6%	9.7%
	+50%	14.9%	17.1%	19.2%
	+100%	24.4%	26.6%	28.7%
	+150%	33.9%	36.1%	38.2%
	+200%	43.4%	45.6%	47.7%

(1) Price required for manufacturer to earn a 12% unlevered IRR over a 10-year period.
(2) Assumes 80% capacity utilization.
(3) Assumes $12,000 / MW-year of SG&A expenses.
(4) Difference between modeled price and Jan-Apr 2024 average import price.
(5) All Module costs other than itemized inputs (which include solar cells, glass, aluminum, and EVA).

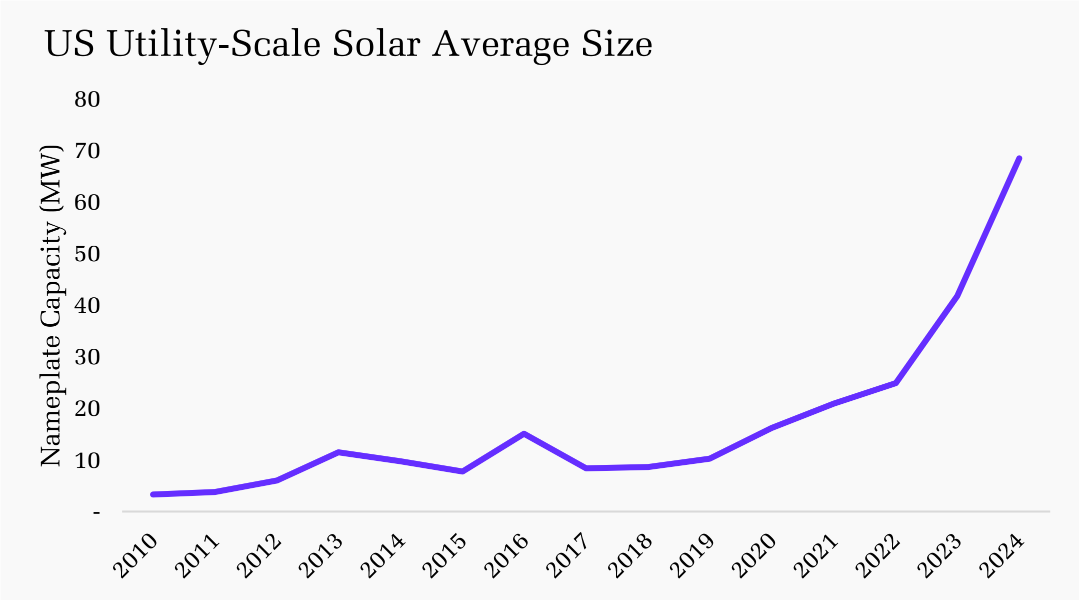
7. Implications for utility-scale solar costs

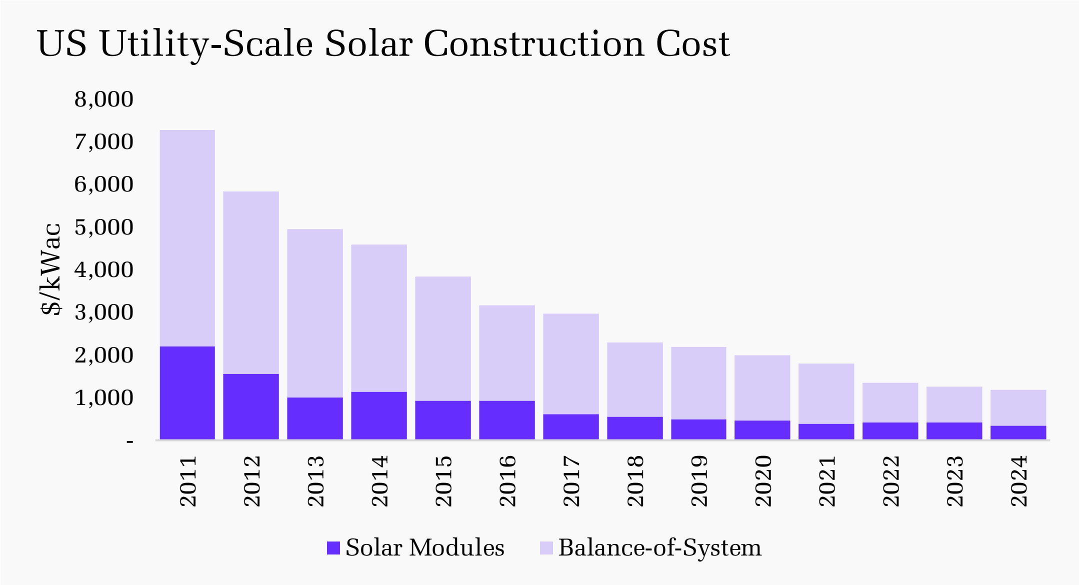
Solar projects, like wind farms, have an almost entirely fixed cost structure. Upfront construction costs are 71% of the LCOE for a utility-scale solar installation in the US before subsidies, or up to 92% including interest and distributions to investors.



Since 2011, the lifetime average cost of power from utility-scale solar projects has fallen by nearly 90 percent, with much of that increase driven by falling construction costs. Learning effects for key components like solar modules and inverters were the main drivers of this trend, but project-level scale economies were also important, as the scale of the average utility-scale solar project increased by a factor of ten.

We estimate that solar modules represent around 30 percent of the construction cost of the typical utility-scale solar project in the US, and roughly the same share of solar's lifetime average cost of electricity. Consulting firm Sargent and Lundy, which provides cost estimates used in the US Energy Information Administration's long-term energy forecasts, pegs the cost of other electrical and mechanical components at a similar 30-percent share of costs, with the remainder allocated to civil and structural work, labor costs, and E&C fees and contingency.


US Utility-Scale Solar Average Size
Nameplate Capacity (MW)
80
70
60
50
40
30
20
10
-
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024


US Utility-Scale Solar Construction Cost
$/kWac
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-
2011
2012
2013
2014
2015
2016
2017
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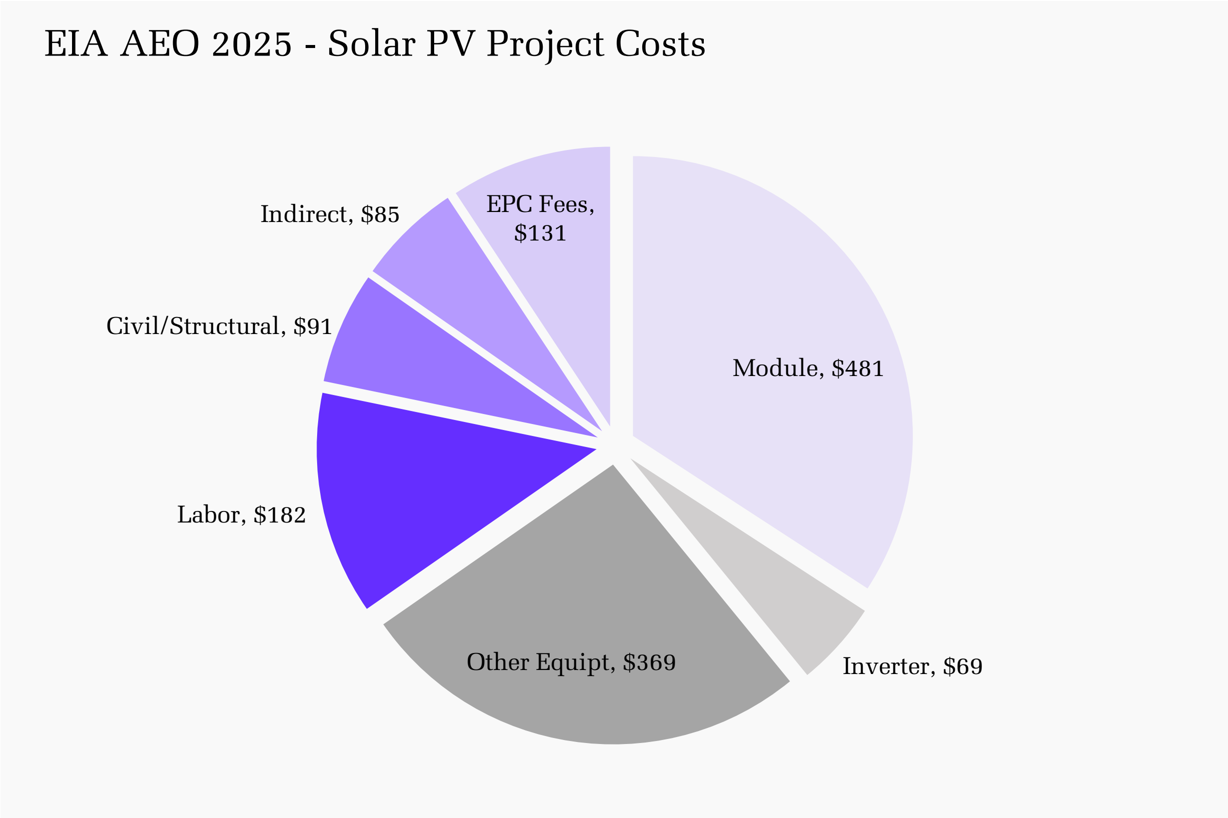
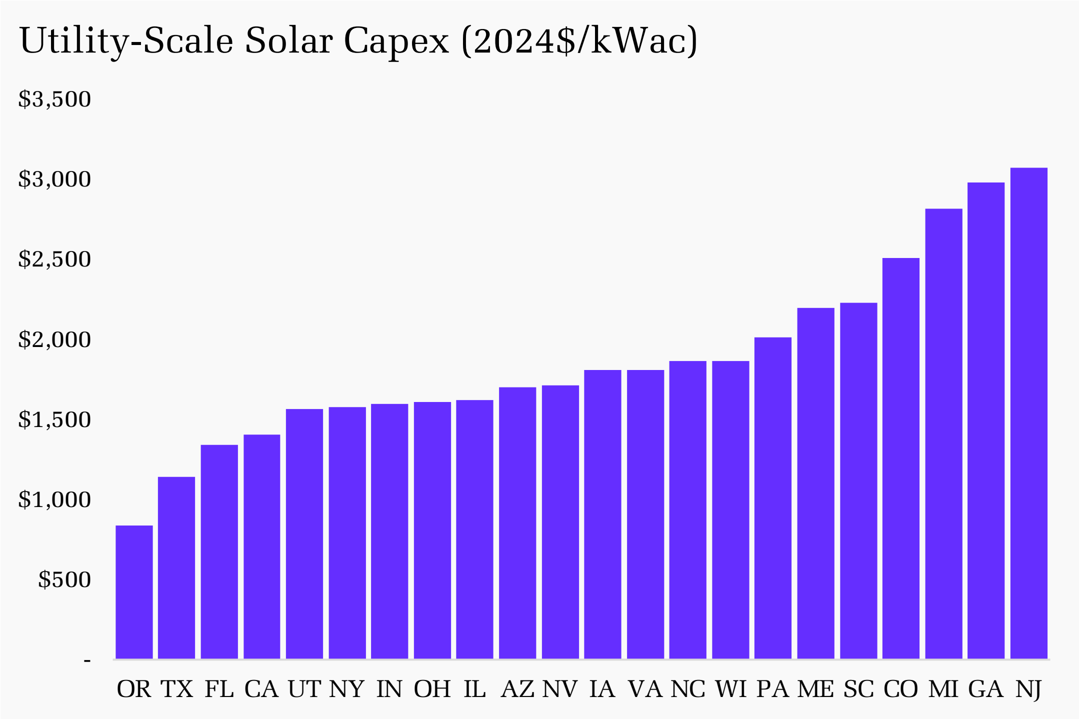
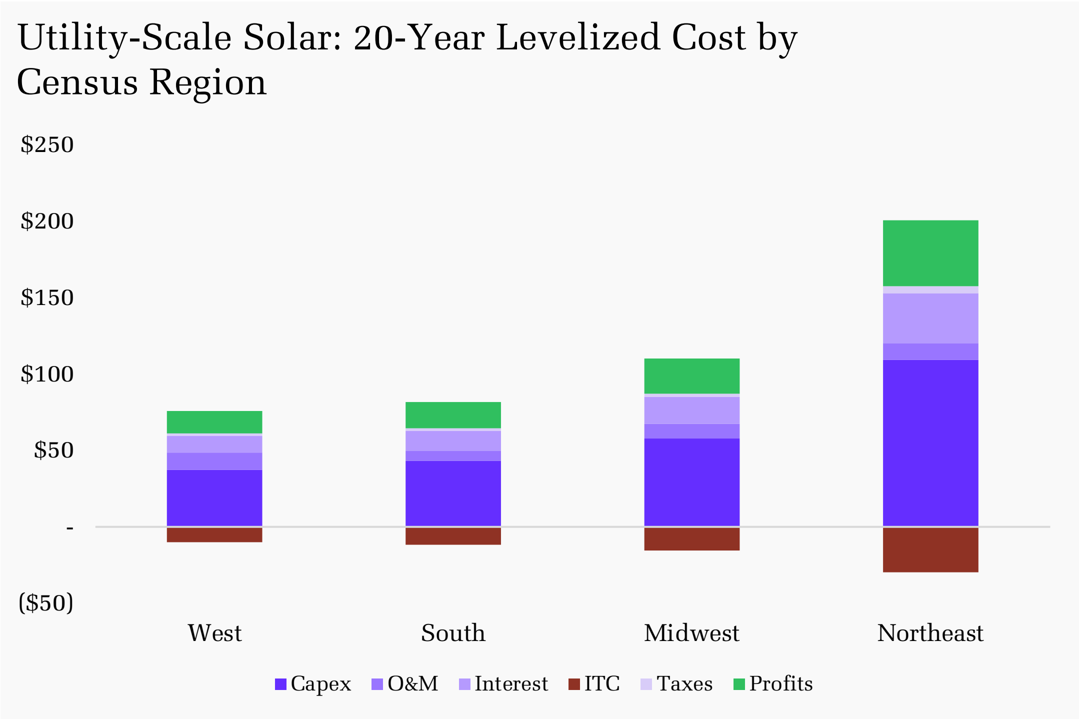
2022
2023
2024
Solar Modules
Balance-of-System



(Note that the example project used in the AEO has a construction cost of ~$1,400 per kW, versus the actual national average of ~$1,350 in 2022, which we estimate has fallen to around ~$1,250 in light of falling module prices)

The upshot is that the impact of a ~0–50% variance in module costs – the range of potential impacts from current trade and industrial policy **— is limited to a +/- 0-15% impact on the levelized cost of energy from a utility-scale solar project.** While significant, the magnitude of the impact is dwarfed by state-level variation in construction costs, which ranges from around $1,000 per kW_{ac} (Oregon, Texas, Florida) to $3,000 per kW_{ac} (Michigan, Georgia, New Jersey).





(EIA, LBNL, JFI Analysis)

8. Future solar material trade flows

The size of the module manufacturing pipeline dwarfs the **40 GW_{dc}** of solar modules installed in the US last year. However, given a much smaller project pipeline for upstream materials — 25.4 GW_{dc} for cells, 14.3 GW_{dc} for wafers, and 8.3 GW_{dc} for ingots, none of which is yet operational — **the US is likely to be a structural importer** of these inputs for the foreseeable future.

Solar module manufacturing is the most "low-tech" step in the solar value chain. Lead times to build module assembly plants are short, and capital requirements are fairly low — often less than $100 per kW_{dc} of manufacturing capacity. The lesson from US solar policy is that **onshoring final assembly of clean energy equipment** can be an effective framework for green industrial policy, and one that in fact often attracts foreign direct investment (FDI) from overseas manufacturers eager to tap into large markets for their upstream output.

However, shifting the location of final assembly, whether in solar or other industries, **will often require maintaining access to lower-cost imports of upstream components** in order to minimize the social and climate cost of higher prices and concomitantly slower deployment of clean energy technologies.

The combination of the IRA's 45X, tariffs on SEA module imports beginning this summer, and domestic content boosters for the IRA's clean energy tax credits will effectively price foreign modules out of the US market. These policy levers are currently well-balanced.

But higher trade barriers on module imports would have little effect on domestic manufacturing capacity, which is already testing the limits of medium-term demand, while longer lead times in upstream solar material investment mean that higher trade barriers on cells and wafers would lead to higher prices without getting the US to self-sufficiency.

The overnight development of a US solar module manufacturing industry highlights the possibilities that effective trade and industrial policy can unlock, but also the importance of targeting **the precise stages in a given value chain can be strategically on-shored** to maximize the upside in domestic jobs and investment, while minimizing the pain of higher costs consumers.

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